Thermal Expansion and Temperature Dependence of Young's Modulus of Nickel-Copper Alloys*

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The thermal expansion coefficient and the temperature coefficient of Young's modulus in nickel-copper alloys have been determined with a vertical dilatometer previously designed by one of the present authors and by means of a vibrator-controlled oscillator system, respectively. And it has been found that the mean linear coefficient of thermal expansion (0°–40°C) vs. composition curve against the composition axis is convex in the ferromagnetic region and concave in the paramagnetic region and also the mean temperature coefficient (0°–40°C) of Young's modulus shows negative values in the whole composition range of the alloys except the maximum value of +2.1 x 10^-4 in the alloy containing 28.85% Cu.

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I. Introduction

In 1936, Nakamura(1) carried out measurements of Young's modulus $E$, the temperature coefficient of the modulus $e$ and the thermal expansion coefficient $\alpha$ for ferromagnetic Ni-Cu alloys by an electromagnet vibration method, and reported that $e$ shows a high positive value of +26 x 10^-5 for the composition of 30.70% Cu. In 1944, following his work, two of the present authors(2) measured the same alloys by a static method, but the experimental results showed no positive values of $e$ except a negative minimum value for compositions near 30% Cu. Such contradictory results may be ascribed primarily to the fundamental difference between the methods of dynamic and static measurements and secondly to the effect of magnetization in Nakamura's measurements due to the use of his specimens as part of the magnetic circuit. Therefore, in order to confirm this point, the present authors have carried out measurements of $e$ in Ni-Cu alloys by using a vibrator-controlled oscillator system(3) free from magnetic field. The experimental results are described in this paper, with the measured data on the thermal expansion of the alloys.

II. Specimens and Experimental Procedure

As the alloying materials, electrolytic Ni and electrolytic Cu were used. Analytical results of their compositions are summarized in Table 1. For the preparation of specimens, appropriate amounts of the metals were melted in an alumina crucible in hydrogen atmosphere with a high-frequency induction furnace and cast into an iron mold 5 mm in inner diameter. The ingot was swaged at room temperature to a rod of 2-mm diameter, from which pieces 10 cm long were cut out as specimens. 21 specimens of different composition were used for the experiment.

Table 1 Analytical results of Ni and Cu used in %

<table>
<thead>
<tr>
<th></th>
<th>Ni</th>
<th>Co</th>
<th>Cu</th>
<th>Fe</th>
<th>Si</th>
<th>Mn</th>
<th>Sb</th>
<th>Pb</th>
<th>S</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni</td>
<td>99.98</td>
<td>0.016</td>
<td>0.001</td>
<td>0.001</td>
<td>0.000</td>
<td>0.000</td>
<td>—</td>
<td>0.000</td>
<td>0.002</td>
<td>0.000</td>
</tr>
<tr>
<td>Cu</td>
<td>0.000</td>
<td>0.000</td>
<td>99.972</td>
<td>0.008</td>
<td>0.009</td>
<td>0.001</td>
<td>0.005</td>
<td>—</td>
<td>0.005</td>
<td>0.000</td>
</tr>
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</table>

All the specimens were heated in vacuum at 900°C for 30 min and then cooled at a rate of 300°C/hr. Young's modulus measurements were carried out at frequencies of 600-800 Hz by use of a vibrator-controlled oscillator system. Thermal expansion measurements were conducted by a horizontal-type dilatometer and a vertical-type dilatometer(4) devised by Kobayashi and one of the present authors. The density was determined by weighing in water.

III. Experimental Results and Discussion

Fig. 1 indicates the temperature vs. linear thermal expansion $\Delta l/l$ curves at 0°-500°C for Ni-Cu alloys containing less than 30.86% Cu. As can be seen in the figure, the temperature vs. $\Delta l/l$ curve for pure Ni shows a distinct knee at the magnetic transformation point, and its curvature at the temperatures above and below the knee is nearly linear although the gradient of the former.

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is greater than the latter. The shape of the temperature vs. Δl/l curves after the addition of Cu to Ni is very similar to that for pure Ni, but the knee shifts gradually toward lower temperatures and becomes unobserved at 30.86% Cu. The mean linear coefficients of thermal expansion at 0°C ~ 40°C for the various compositions are illustrated in Table 2 and Fig. 2.

As shown in Fig. 2, the shape of the α vs. composition curves against the composition axis is slightly convex in the ferromagnetic range and is concave in the paramagnetic range, in fairly good agreement with the results measured by two of the present authors. The variation in density D is nearly negligible in all the alloys investigated.

Fig. 3 shows the change in the ratio (f_t/f_0)^2 with temperature, where f_t and f_0 are the resonant frequencies at t°C and 0°C. As can be seen in the figure, with rising temperature, (f_t/f_0)^2 for pure Ni at first decreases linearly, attains a minimum value in the vicinity of 155°C, and then increases linearly. Later the value reaches a maximum at the magnetic transformation point. With increasing Cu addition to Ni, the variation in number of frequencies become lessened gradually and is not observed for the composition of 30.86% Cu near the magnetic transformation point.

The composition dependence of E at room temperature and e derived from Fig. 3 is shown in Fig. 2. The figure shows that with increasing Cu content, the E value of 19.95 × 10^5 kg/cm² for pure Ni decreases gradually in the ferromagnetic region and linearly in the paramagnetic region with some rapidity. In the Nakamura's measurement the value of E decreases somewhat faster the present authors'. Meanwhile, the measured data by two of the present authors indicate that the value of E, 17.2 × 155 kg/cm², becomes greater with increasing Cu content, thus showing a pronounced maximum at compositions near the ferromagnetic to paramagnetic transition. These results
are in conspicuous disagreement with those of the present authors. Although numerous $E$ measurements have hitherto been carried out for Ni–Cu alloys\(^5\), it is noted that there are remarkable differences in the measured data within the ferromagnetic region by investigators. This is probably due to the difference in the purity, shape and crystal grain size of specimens or the measuring method.

The value of $e$ for pure Ni is also found to be $-84.0 \times 10^{-5}$. With the addition of Cu, the value is lowered rapidly, change to a positive sign, and steeply rises to a maximum value of $+2.1 \times 10^{-5}$ at the composition of about 35% Cu. The positive value is then lowered rapidly, changes to a negative sign, and reaches a maximum of $-31.5 \times 10^{-5}$ with a pronounced enlargement. Further the negative value gently decreases, but after passing through the minimum value of $-14.5 \times 10^{-5}$ at 80% Cu, it is enlarged to a value of $-33.5 \times 10^{-5}$ for pure Cu. As shown in the figure, this result is not consistent with the experimental data of Nakamura and also of two of the present authors. The causes for such inconsistency in the measured data are considered as follows: In the present study a vibrator-controlled oscillator system free from applied fields was used to carry out $E$ measurements at frequencies of 600–800 Hz, whereas Nakamura conducted dynamic measurements of $E$ with the electromagnet vibration method using the specimens as part of the magnetic circuit. On the other hand, two of the present authors statically measured $E$ with spiral-shaped specimens. The experimental results of the present authors were already presented at the 1963 Annual Meeting of the Japan Institute of Metals held at Nagoya. Later in 1965, Orlov and Fedotov\(^6\) measured Young’s modulus and the rigidity modulus at $0^\circ-800^\circ$C for pure Ni, pure Cu and Ni–Cu alloys containing 0.3, 7, 12, 36, 65 and 78% Cu. However, since their experimental results do not provide information on anomalies for compositions near 30% Cu, no comparison can be made with the measured data of the present authors.

IV. Conclusions

Measurements of Young’s modulus and its temperature coefficient, the mean linear coefficient of thermal expansion and the density were carried out for Ni–Cu alloys in the annealed state, with the results summarized as follows:

1. The mean linear coefficient of thermal expansion vs. composition curves at $0^\circ-40^\circ$C against the composition axis are concave in the ferromagnetic region and convex in the paramagnetic region.

2. The density at $20^\circ$C shows very little variation at all compositions investigated.

3. The Young’s modulus vs. composition curves at $20^\circ$C against the composition axis are concave in the ferromagnetic region and are nearly linear in the paramagnetic region.

4. The mean temperature coefficient of Young’s modulus at $0^\circ-40^\circ$C shows a negative value at all compositions except the positive maximum value of $+2.1 \times 10^{-5}$ measured near 29.85% Cu.
